



Adoption and Impact of Green Manufacturing Practices on Sustainable Industrial Development in Anambra State, Nigeria

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Article Info	ABSTRACT
<p>Corresponding Author: Aguh Patrick Sunday E-mail: ps.aguh@unizik.edu.ng</p>	<p>This study examines the adoption and impact of green manufacturing practices on sustainable industrial development in Anambra State, Nigeria. Focusing on major industrial hubs such as Nnewi, Onitsha, and Awka, the research explores how local industries integrate sustainable production strategies, including renewable energy use, lean production, waste reduction, and eco-friendly material adoption, within a context of environmental, economic, and social challenges. Findings reveal that while large firms have made notable progress, installing solar systems, improving process efficiency, and complying with export-driven eco-standards, small and medium-sized enterprises (SMEs) face significant barriers, including high capital costs, limited technical expertise, outdated machinery, and weak policy enforcement. Despite these challenges, the study demonstrates that green practices yield substantial benefits: reducing greenhouse gas emissions and material waste by up to 15–20%, lowering energy costs, enabling access to green product markets, and fostering new employment opportunities in waste management, renewable energy, and environmental consulting. The paper underscores the pivotal role of industrial engineers in driving eco-efficiency through lean-green integration and digital tools, while highlighting the need for robust policy frameworks, financial incentives, and capacity-building initiatives. Ultimately, the research positions Anambra State as a potential model for sustainable industrial growth in Nigeria, aligning with the United Nations Sustainable Development Goals (SDGs) and national climate commitments under the Paris Agreement.</p> <p>Keywords: Green Manufacturing, Sustainable Industrial Development, Renewable Energy, Lean-Green Integration, Circular Economy Models, Environmental Policy</p>

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INTRODUCTION

Background on Green Manufacturing

Green manufacturing is increasingly recognized as a crucial paradigm in industrial production, emphasizing processes and technologies designed to minimize negative environmental impacts while promoting efficiency and sustainability. This concept represents a significant alignment of industrial growth with environmental stewardship, focusing on

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energy conservation, waste minimization, and resource efficiency. The relevance of green manufacturing is underscored by the pressing global issues surrounding climate change, resource depletion, and pollution, thereby positioning it as an integral component of sustainable industrial strategies. At its core, green manufacturing entails adopting practices that reduce environmental footprints and enhance resource efficiency. Strategies may include utilizing renewable energy sources, recycling materials, and implementing cleaner production techniques. For instance, adopting advanced manufacturing technologies such as Industry 4.0 can facilitate substantial resource savings and carbon footprint reductions, particularly when integrated with digital economy investments that promote low-carbon development (Luo et al., 2022; Tan et al., 2023; Nwamekwe et al., 2024). Advanced manufacturing solutions not only reduce waste and energy consumption but also encourage companies to innovate in product design, leading to the development of more sustainable products (Saxena et al., 2023).

The increasing prevalence of environmental regulations and the growing pressure from consumers for sustainable products have driven companies to adopt green manufacturing practices. Businesses are recognizing that sustainable practices can enhance their competitive advantage in the marketplace, drive consumer loyalty, and fulfill their corporate social responsibility commitments. Studies indicate that industries adopting green practices often see improved financial performance due to lower operational costs and increased efficiency (Borland et al., 2019). Moreover, the integration of sustainable practices helps in building resilience against market fluctuations and regulatory changes (Nwamekwe et al., 2025).

Moreover, the notion of sustainability in manufacturing extends beyond ecological considerations to encompass social and economic dimensions. Sustainable manufacturing practices can lead to broader societal benefits, including job creation in green sectors and improved public health outcomes through reduced pollution and waste disposal issues (Igbokwe et al., 2024; Okpala et al., 2025). Therefore, aligning green manufacturing with the UN Sustainable Development Goals (SDGs) further emphasizes its importance in promoting both industrial sustainability and socio-economic development (Nwamekwe et al., 2025).

The shift towards green manufacturing reflects a conscious effort by industries to embed sustainability into their core operational strategies. It marks a transformation in how manufacturers conceive of their responsibilities, advocating for a balance between economic success and environmental preservation. By leveraging innovations in technology and production processes, the manufacturing sector can contribute significantly to sustainable industrial development, especially in regions like Anambra State in Nigeria, where there is a growing need for sustainable practices in response to both local and global environmental challenges (Bianchi et al., 2023; Adamik & Sikora-Fernandez, 2021).

1. Importance of Sustainable Industrial Development

Sustainable industrial development plays a critical role in promoting both economic resilience and environmental protection. It ensures that growth does not excessively exploit natural resources or create social disparities, thereby fostering a balance between productivity, eco-efficiency, and social responsibility (Malik et al., 2020; Afum et al., 2020). Specifically for regions like Anambra State, Nigeria, the integration of green manufacturing

practices is vital to address pollution, inefficient energy use, and poor waste management (Oláh et al., 2020).

Adopting green practices enhances organizational sustainability by improving operational efficiency and driving innovation (Jamal et al., 2021; Nwaulune, 2024). Moreover, the alignment of Industry 4.0 technologies with sustainable development goals can significantly enhance environmental sustainability, thereby creating a conducive environment for economic growth without compromising ecological integrity (Oláh et al., 2020; Afum et al., 2020; Hejazi et al., 2023). As Nigeria's industries increasingly acknowledge the importance of sustainable practices, they can contribute positively to socio-economic growth while ensuring environmental protection for future generations (Jamal et al., 2021; Nwamekwe et al., 2020; Shurrab et al., 2019).

Rationale for Focusing on Anambra State

The rationale for focusing on Anambra State in the context of sustainable industrial development is multifaceted. As one of Nigeria's most industrialized southeastern states, Anambra hosts significant manufacturing hubs such as Nnewi, known for auto parts production, Onitsha for consumer goods, and Awka for small-scale manufacturing. However, these industries face critical challenges, including waste mismanagement, outdated technologies, and energy inefficiencies, which can obstruct sustainable growth. Examining Anambra's industrial landscape facilitates understanding the complexities of the transition towards green manufacturing practices. This provides vital insights into how local industries might adapt to or resist such transitions, reflecting broader trends in developing regions. Furthermore, the role of industrial engineers as agents of change becomes pivotal in mitigating adverse environmental impacts while fostering innovation and efficiency in manufacturing. Therefore, Anambra represents a significant case for exploring the adoption of green practices and their implications for sustainable development in Nigeria's evolving industrial context.

Objectives and Scope of the Review

This review will explore the current adoption levels of green manufacturing practices in Anambra State, examines their environmental, economic, and social impacts, and evaluates the role of industrial engineers in promoting sustainable development. It will also identify gaps, challenges, and opportunities for policy interventions and technological innovation as described in the thematic chart below (figure 1).

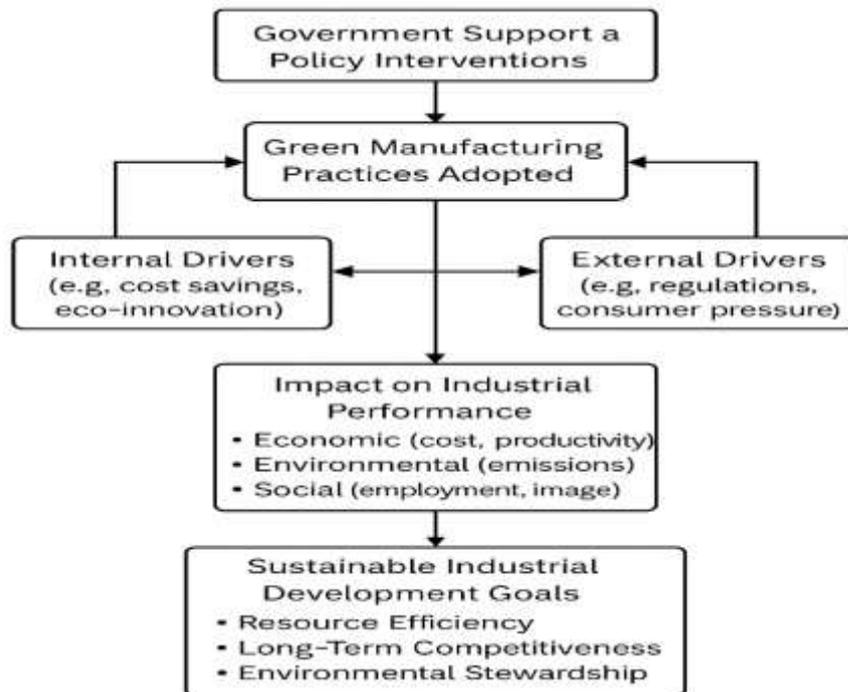


Figure. 1: Thematic Chart: Green Manufacturing and Sustainable Industrial Development

2. Overview of Green Manufacturing Practices

Definition and Core Principles

Green manufacturing is defined as a sustainable approach that integrates environmental considerations into manufacturing processes. It emphasizes minimizing the negative environmental impacts of production while enhancing economic performance and product quality. The core principles of green manufacturing include resource efficiency, waste reduction, lifecycle thinking, and pollution prevention, all aimed at promoting sustainable industrial practices (Caldera et al., 2019).

A fundamental aspect of green manufacturing is the commitment to using fewer resources and minimizing waste, thereby optimizing production processes. This aligns with lean manufacturing principles, which advocate for efficiency and value creation (Kalyar et al., 2019). Additionally, green manufacturing encourages the use of low-impact materials that are biodegradable or recyclable, thus reducing the environmental footprint associated with raw material extraction and product disposal, although specific studies emphasizing this need further verification (Arinaitwe et al., 2024).

1. **Reduced Resource Consumption:** Green manufacturing can be defined as an innovative approach oriented towards maximizing resource efficiency while simultaneously minimizing waste and environmental impacts associated with manufacturing processes. A core principle of green manufacturing is reduced resource consumption, which encompasses the strategic management and utilization of materials, energy, and water throughout the production lifecycle. This principle is essential for fostering sustainability in manufacturing within regions such as Anambra State, Nigeria. By adopting practices that promote reduced resource consumption, manufacturers can significantly decrease their ecological footprint. This includes employing energy-efficient technologies, optimizing processes to reduce material

waste, and managing water use effectively (Siddique, 2024; Mehta et al., 2025). For instance, energy savings can be achieved through innovative approaches such as integrating advanced manufacturing technologies and predictive maintenance, which collectively optimize resource utilization while maintaining production efficiency and quality (Okeagu et al., 2024).

2. **Pollution Prevention and Control:** It is a fundamental aspect of green manufacturing, particularly in developing regions like Anambra State, Nigeria. This approach emphasizes proactive measures that minimize the generation of pollutants at their source, thereby reducing adverse environmental impacts associated with industrial activities. Implementing pollution prevention strategies in manufacturing processes helps companies not only comply with environmental regulations but also fosters a more sustainable operational model (Borha & Olujobi, 2023; Ogunmodede et al., 2024). Green manufacturing practices, through pollution control mechanisms, enable the reduction of harmful emissions and waste generation. These practices include using eco-friendly materials, adopting cleaner production technologies, and improving process efficiencies. For example, advanced manufacturing technologies, such as cleaner production techniques and waste minimization strategies, can significantly reduce waste generation and lower greenhouse gas emissions (Nwamekwe et al., 2025; Ohiomah & Aigbavboa, 2020). Furthermore, by implementing robust waste management systems, manufacturers can transform waste products into resources, thus minimizing the overall environmental footprint and enhancing operational efficiency (Yakubu et al., 2022).
3. **Lifecycle Thinking in Product Design:** It is an essential aspect of green manufacturing, aiming to take a holistic view of a product's environmental impact throughout its entire lifecycle (Malik et al., 2020). This approach involves considering all phases—from raw material extraction and processing to production, use, and end-of-life disposal or recycling. In Anambra State, Nigeria, where industrial practices are rapidly evolving, integrating lifecycle thinking can significantly enhance the sustainability of local manufacturing processes. Implementing lifecycle thinking requires manufacturers to focus on minimizing resource consumption and waste generation at each stage of a product's life. For example, companies can design products for durability, efficiency, and ease of recycling, thus reducing the environmental impact associated with material extraction and processing (Afum et al., 2020). By adopting eco-design principles, manufacturers can foster innovation as they seek to create products that are not only functional but also environmentally friendly (Afum et al., 2020).
4. **Use of Clean Energy and Low-Impact Materials:** The use of clean energy and low-impact materials is central to the principles of green manufacturing, and it plays a significant role in promoting sustainable industrial development in areas like Anambra State, Nigeria. Clean energy refers to the utilization of renewable energy sources—such as solar, wind, and hydroelectric power—aimed at reducing greenhouse gas emissions associated with manufacturing processes (Kiswanto et al., 2023). Transitioning to clean energy not only cuts operational costs for industries but also enhances their resilience against fluctuations in fossil fuel prices and regulatory changes pertaining to carbon emissions (Nwamekwe and Okpala, 2021). Similarly, adopting low-impact materials is crucial for reducing the environmental footprint of

manufacturing operations. This includes biobased and recycled materials that minimize resource depletion and energy consumption during their lifecycle. For example, utilizing advanced biodegradable materials, such as cellulose or natural fibre composites, can lead to significant reductions in harmful emissions and waste during production and disposal stages (Frohn-Sørensen et al., 2021; Foroughi et al., 2021). Integrating such materials ensures that manufacturing processes align with the principles of sustainability while meeting the growing consumer demand for eco-friendly products (Barik & Mondal, 2025; Pell et al., 2021).

Global Trends and Emerging Technologies

Globally, the manufacturing sector is undergoing a significant transformation as it increasingly adopts cleaner production technologies. Key trends include the integration of renewable energy sources, implementation of closed-loop systems, and reliance on environmentally friendly raw materials—all essential components of green manufacturing practices. Closed-loop systems, which recycle waste as input rather than sending it to landfills, have gained traction for their ability to minimize resource consumption and pollution (Umar et al., 2021). Moreover, the integration of renewable energy, such as wind, solar, and biomass, is crucial in reducing carbon footprints associated with traditional manufacturing processes. This shift enhances efficiency and ensures that industries are less dependent on finite fossil fuels, thus promoting sustainability (D'Angelo et al., 2022; Afum et al., 2020). The adoption of clean energy is increasingly seen as a competitive advantage, aligning operational practices with the rising consumer demand for eco-friendly products and services (Afum et al., 2020). In addition to these technological advancements, Industry 4.0 tools—such as the Internet of Things (IoT), Artificial Intelligence (AI), and big data analytics—are driving real-time energy monitoring and predictive maintenance in manufacturing. These technologies allow manufacturers to optimize energy use, enhance efficiency, and reduce operational costs by anticipating maintenance needs, thereby preventing energy loss and production delays (Nazir et al., 2024). This ongoing evolution highlights the vital role of emerging technologies in shaping the future landscape of green manufacturing while contributing to a more sustainable industrial development trajectory.

Relevance to Industrial Engineering Functions

Industrial engineers play a pivotal role in advancing green manufacturing practices, particularly in the context of sustainable industrial development. Their core functions encompass designing, managing, and optimizing systems to achieve maximum efficiency while minimizing waste. This alignment is critical as industries—including those in Anambra State, Nigeria—move towards sustainable practices that reduce environmental impact and improve economic performance (Igbokwe et al., 2024). One significant function of industrial engineers is their implementation of lean production methodologies, which focus on resource efficiency and waste reduction. Lean principles streamline production processes, thereby limiting excess and enhancing overall productivity. By optimizing workflows and eliminating non-value-adding activities, industrial engineers ensure that manufacturing systems operate at peak efficiency while adhering to green manufacturing standards (Wellbrock et al., 2020). Moreover, industrial engineers are instrumental in supply chain optimization. By integrating sustainability metrics into supply chain management, they can identify strategies that reduce

emissions and foster the use of environmentally friendly materials. This is particularly critical as enterprises grapple with the need for greener supply chains that align with global environmental standards (Qiu et al., 2021). Additionally, process reengineering, another essential function of industrial engineering, involves redesigning processes to eliminate waste and improve sustainability. Industrial engineers apply advanced analytical tools, such as big data and AI, to monitor processes and predict maintenance needs, further enhancing efficiency and sustainability in operations (Tan et al., 2023).



Figure. 2: The Overview of Green Manufacturing Practices

3. Industrial Landscape of Anambra State

Key Manufacturing Hubs

Nnewi: Nnewi, often referred to as the automotive parts manufacturing capital of Nigeria, represents a critical node in the industrial landscape of Anambra State. This city hosts a myriad of manufacturing enterprises, particularly in the automotive sector, which contributes significantly to the local and national economy. The concentration of automotive parts manufacturers in Nnewi illustrates the region's entrepreneurial spirit, as local businesses have capitalized on the growing demand for vehicle components both within and outside Nigeria (Ekesiobi & Dimnwobi, 2020).

In Nnewi, the manufacturing landscape is characterized by small and medium enterprises (SMEs) that play a vital role in job creation and economic development. These companies often adopt innovative production techniques, leveraging local resources and labour to meet market needs. The automotive parts industry in Nnewi not only provides essential components for vehicles but also drives ancillary sectors such as logistics and distribution, contributing to the overall economic framework of Anambra State (Uzoamaka & Yvette, 2023).

Despite the vibrancy of the automotive manufacturing sector, challenges remain, including energy inefficiencies and inadequate waste management. These issues highlight the importance of integrating green manufacturing practices to enhance sustainability and operational efficiency. By shifting towards cleaner production processes, Nnewi's manufacturers can reduce their environmental impact and align with global trends aimed at promoting sustainable industrial development (Ekesiobi & Dimnwobi, 2020). Furthermore, as Nnewi continues to thrive as a manufacturing hub, it serves as a relevant case study for understanding the adoption of green practices in the industrial sector. The implementation of

sustainability metrics and eco-friendly manufacturing techniques could significantly enhance the competitive edge of Nnewi's automotive parts manufacturers and pave the way for a more resilient industrial ecosystem in Anambra State (Uzoamaka & Yvette, 2023).

Onitsha: The city of Onitsha in Anambra State, Nigeria, stands as a significant commercial hub characterized by high-volume production in consumer goods, food processing, and packaging. Renowned for its bustling markets and trading activities, Onitsha contributes substantially to both regional and national economies, highlighting its integral role in the industrial landscape of Anambra State. Onitsha's manufacturing sector is diverse, encompassing various industries from consumer goods, like textiles and household products, to food processing and packaging. This diversity not only harnesses local resources but also creates numerous job opportunities, thus driving economic growth. The city's strategic location along the Niger River provides critical logistical advantages, facilitating easy transport of goods and raw materials, which is vital for manufacturing operations.

However, the rise in manufacturing activities has also led to pressing environmental challenges, particularly concerning waste management and resource consumption. As such, there is an increasing need for integrating green practices into the manufacturing processes in Onitsha to enhance sustainability. Manufacturers must consider adopting cleaner production technologies and environmentally friendly materials to mitigate pollution and reduce their ecological footprint. Implementing green practices can facilitate compliance with emerging regulatory frameworks focusing on sustainability, thus positioning Onitsha's industries favourably within both local and international markets. Furthermore, Onitsha's vibrant manufacturing sector offers a robust platform for innovation and the adoption of Industry 4.0 technologies. The integration of tools such as artificial intelligence (AI), big data analytics, and the Internet of Things (IoT) can optimize production efficiency, enhance product tracking, and improve resource management. Leveraging these technologies in manufacturing processes could significantly contribute to Onitsha's transition towards sustainable industrial development.

Awka: Awka, the capital of Anambra State, is characterized by a vibrant industrial landscape predominantly composed of SMEs that specialize in metal works, furniture production, and electronics. This diversification in manufacturing not only stimulates the local economy but also provides a critical platform for the adoption of sustainable industrial practices aimed at enhancing operational efficiencies and minimizing environmental impacts (Yacob et al., 2019).

In the sector of metal works, manufacturers in Awka produce a variety of products from basic construction materials to intricate metal fabrications. The demand for quality metalwork has seen numerous local firms investing in modern techniques and technologies to improve productivity and reduce waste. Implementation of green manufacturing practices in this segment could further help these businesses reduce energy consumption and harmful emissions, aligning with global sustainability goals (Umar et al., 2021). The furniture industry in Awka is another key player, benefiting from the region's rich natural resources. Local artisans and companies are known for their craftsmanship and innovative designs, which have the potential to penetrate broader markets. By adopting eco-friendly materials and minimizing waste through recycling, the furniture sector can enhance its sustainability profile while appealing to an increasingly environmentally conscious consumer base (Afum et al., 2020).

In the electronics domain, SMEs in Awka are emerging with a focus on the assembly and distribution of various electronic products. As the market for electronics evolves, there is a pressing need for these companies to adopt green manufacturing initiatives, which involve efficient production techniques that prioritize energy efficiency and the use of recyclable materials, thereby reducing the environmental footprint of their operations (Nazir et al., 2024). While the industrial landscape of Awka presents numerous opportunities for growth, it is also faced with challenges such as outdated technologies and limited access to environmentally friendly materials. However, integrating green practices can lead to substantial improvements in resource efficiency, operational competitiveness, and sustainability performance. The role of industrial engineers and policymakers can be transformative in supporting Awka's manufacturing sector as it transitions into greener production methodologies, facilitating a more sustainable industrial development trajectory for Anambra State at large (D'Angelo et al., 2022).

Environmental Challenges in Local Industries

These hubs struggle with the following:

1. Poor solid and hazardous waste disposal: Local industries in Anambra State face significant environmental challenges, particularly concerning poor management of solid and hazardous waste disposal. These challenges are critical as they not only affect public health and environmental quality but also hinder the adoption of sustainable manufacturing practices within key industrial hubs like Nnewi and Onitsha. Poor solid waste disposal practices in these industrial hubs often result from inadequate infrastructure for waste management. Many local industries rely on outdated disposal methods such as uncontrolled dumping, open-air incineration, and non-compliant landfills, leading to negative repercussions such as air and water pollution, land degradation, and greenhouse gas emissions (Nwamekwe and Nwabunwanne, 2025). Specifically, Anambra State's manufacturing sector generates substantial amounts of solid waste, much of which ends up in poorly managed dumpsites, exacerbating pollution crises and creating health hazards for nearby communities (Ugwu et al., 2020).

Moreover, hazardous waste management remains a pressing concern. Many local industries generate hazardous materials, particularly in sectors like electronics and food processing, yet lack the necessary infrastructure and guidelines for their safe disposal and management (Yusuf et al., 2018). Hazardous wastes, which may include batteries, electronic components, and packaging materials, pose severe risks to both environmental and public health when not handled properly. The perception that waste management is the sole responsibility of government authorities contributes to negligence among waste producers, leading to widespread improper disposal practices that can trigger disease outbreaks and long-term health complications (Yusuf et al., 2018). Insufficient funding, lack of proper regulations, and weak enforcement mechanisms further complicate waste management challenges in Anambra State. These factors underline the urgent need for the adoption of integrated waste management systems that not only incorporate technological solutions but also community education and regulatory frameworks aimed at sustainable environmental practices (Ardiana et al., 2022).

Fostering a culture of responsible waste disposal and management is essential for industries in Anambra State to fully embrace green manufacturing practices. Such measures

will not only enhance environmental sustainability but also improve the economic resilience of local industries, enabling them to compete in both national and international markets (Patrick et al., 2022). High dependency on fossil-fuel generators: Local industries in Anambra State face significant environmental challenges, particularly their high dependency on fossil-fuel generators for energy supply. This reliance arises from the limited availability of reliable electricity from the national grid, compelling many manufacturers to resort to diesel and petrol-powered generators. This practice intensifies operational costs while simultaneously posing severe environmental risks, including greenhouse gas emissions and air pollution.

2. Limited wastewater treatment systems: Local industries in Anambra State encounter significant environmental challenges, notably due to the limited wastewater treatment systems in place. This inadequacy poses a threat to the environment and public health and hinders the overall sustainability of industrial practices. The limited capacity for effective wastewater management in Anambra's industrial hubs results in increased pollution levels in local water bodies. Many manufacturing facilities discharge untreated or inadequately treated wastewater directly into rivers and streams, leading to the contamination of water sources that are vital for both human consumption and aquatic life. According to research, improper wastewater management contributes to numerous environmental issues, including the proliferation of waterborne diseases and the degradation of ecosystems (Jones et al., 2021). As wastewater production continues to rise with industrial activity and urban development, robust wastewater management strategies become increasingly essential.

Moreover, the absence of comprehensive wastewater treatment facilities limits the ability of these industries to recycle and reuse water effectively. Efficient wastewater treatment systems can significantly reduce the demand for freshwater resources, addressing scarcity issues while promoting sustainability (Jones et al., 2021; Habib et al., 2021). The lack of investment in these systems often stems from financial constraints, insufficient regulatory frameworks, and a general underestimation of the environmental impacts caused by inadequate wastewater management practices. In seeking to improve their environmental performance, local industries must adopt best practices for wastewater treatment that align with green manufacturing principles. These practices could include the integration of advanced oxidation processes, biological treatment methods, and the use of green materials for enhanced wastewater processing (Nwamekwe and Igbokwe, 2024). By investing in modern wastewater treatment technologies, industries can not only minimize their environmental footprint but also enhance their productivity and compliance with environmental regulations. Moreover, adopting well-designed wastewater treatment systems could pave the way for industries in Anambra State to embrace circular economy principles. Systems that safely treat wastewater can enable the recovery of resources, thereby transforming waste into a valuable commodity for reuse in other processes or applications (Rabia et al., 2024).

3. Outdated, inefficient machinery: Local industries in Anambra State face a myriad of environmental challenges, and one critical issue is their reliance on outdated and inefficient machinery. This reliance not only hampers economic performance but also exacerbates environmental degradation throughout the manufacturing process. Outdated machinery often operates below optimal efficiency, leading to excessive energy consumption and increased emissions. Many manufacturing facilities in

Anambra continue to utilize older machines that lack modern energy-saving technologies. This inefficiency contributes to a higher carbon footprint, as these machines typically consume more fuel or electricity than their modern counterparts (Okpala et al., 2024). Consequently, the transition to newer, energy-efficient technologies could significantly reduce greenhouse gas emissions and improve environmental sustainability. Moreover, the inefficiency of aging equipment can lead to increased waste generation. These machines may produce more defective products, requiring reprocessing or disposal, which strains local waste management systems (Nwamekwe et al., 2025). In industries where margins are already thin, the resulting increase in waste and operational costs makes it challenging for local businesses to compete on a broader scale. Without investment in modern machinery, these industries may struggle to implement green manufacturing practices effectively, undermining efforts toward sustainable industrial development.

The situation is further complicated by financial constraints that limit the ability of many firms to invest in new equipment. Local manufacturers often cite the high upfront costs associated with replacing outdated systems as a barrier to modernization. However, failing to invest in efficient technologies can lock companies into cycles of inefficiency that not only affect their bottom lines but also their ability to adopt environmentally friendly practices. Encouraging investment in advanced machinery is essential for overcoming this challenge. The introduction of financial incentives, government support, and partnerships with technology providers could facilitate the transition toward modern equipment that promotes energy efficiency and reduces waste. Furthermore, aligning local industries with the principles of Industry 4.0—characterized by smart manufacturing and automation—can help these businesses optimize production processes, minimize environmental impact, and enhance sustainability (Jianina, 2023).

Existing Policy and Regulatory Framework

In Anambra State, Nigeria, while there are several policies aimed at environmental protection and sustainable industrial practices, significant gaps remain in their enforcement and application at the state level. One of the key pieces of legislation is the National Environmental Standards and Regulations Enforcement Agency (NESREA) Act, which establishes guidelines for environmental protection across various sectors, including manufacturing. However, enforcement of these regulations is often weak, leading to inadequate compliance and a continued reliance on environmentally harmful practices. Local industries frequently operate without sufficient oversight from regulatory bodies, which calls into question the effectiveness of the existing framework in promoting green manufacturing practices. Moreover, Anambra State's own industrial policy lacks explicit provisions for green standards or incentives. This absence undermines the potential for businesses to transition towards more sustainable practices, as there are no clear guidelines or financial motivators that encourage the adoption of environmentally friendly technologies. In many cases, the lack of structured incentives diminishes the urgency for industries to integrate green practices into their operations. Research has shown that the absence of strong regulatory frameworks and incentives can severely inhibit businesses from investing in necessary green technologies, effectively limiting the scope of sustainable development efforts in these hubs.

Furthermore, existing policies often do not adequately address the specific environmental challenges faced by local industries, such as poor waste management, energy inefficiency, and a dependency on outdated machinery. A comprehensive approach that includes explicit provisions for green standards, alongside financial and technical incentives, is essential for guiding industries toward sustainability. Stakeholders, including government entities, industry leaders, and environmental advocates, must collaborate to create a robust regulatory framework that facilitates the transition to greener manufacturing and enhances the state's overall environmental performance. The design of any such framework should also consider the unique context of Anambra's industrial landscape, recognize the needs of SMEs and offer tailored incentives that support their growth while promoting sustainability. Effective communication of available resources and incentives can bolster awareness and engagement among local businesses, driving the adoption of green practices.

4. Adoption of Green Practices in Anambra Extent of Adoption among SMEs and Large Firms

The adoption of green manufacturing practices in Anambra State varies significantly between large firms and SMEs. Large firms have made progress in integrating green practices; for instance, they have begun installing solar panels and utilizing cleaner fuels, reflecting a growing awareness of environmental sustainability and regulatory compliance. However, the journey toward greener operations is not uniform across the industrial spectrum, particularly when contrasting large firms with SMEs, which face distinct challenges. SMEs in Anambra are lagging in their adoption of green manufacturing practices due to several factors, including cost constraints, limited awareness, and inadequate access to financing. The financial burden associated with upgrading to energy-efficient machinery poses a significant hurdle for these enterprises. Many SMEs continue to operate energy-inefficient machines and engage in unsustainable waste disposal methods, undermining their potential contributions to environmental sustainability. The disparity in green practice adoption can partly be attributed to the relative lack of resources and expertise that SMEs possess compared to larger firms, which often have dedicated teams focused on sustainability initiatives.

Another crucial issue is the limited understanding of the benefits associated with green practices among SME owners and managers. Research indicates that fostering a culture of knowledge-sharing and awareness about environmental issues is essential for enhancing the adoption of green innovations. In many cases, SMEs may not fully recognize the operational efficiencies and market advantages that come from implementing sustainable practices. This creates a cycle where the perception of high initial costs deters SMEs from investing in green initiatives. Additionally, the regulatory framework in the region lacks robust enforcement mechanisms that could incentivize SMEs to adopt greener practices. Much of the environmental legislation and guidelines, such as those provided by the NESREA, are not adequately communicated or enforced at the local level, resulting in minimal compliance among SMEs. Consequently, many SMEs perceive compliance with environmental regulations as a low priority, which further diminishes the urgency for transitioning to sustainable practices.

To bridge the gap between large firms and SMEs in the adoption of green practices, a more supportive policy environment is needed. This includes creating tailored financial

incentives, such as grants or low-interest loans for investments in energy-efficient technologies, as well as providing educational programs aimed at raising awareness about the benefits of green manufacturing. Partnerships with larger firms that are already implementing green practices may also offer SMEs opportunities to learn and grow through knowledge transfer and shared resources.

Case Examples or Survey Highlights

Preliminary studies and anecdotal evidence from industrial clusters in Nnewi indicate that while some firms have implemented basic energy-saving measures, such as the installation of energy-efficient lighting and minor upgrades to heating and cooling systems, comprehensive green frameworks are largely absent. This trend is reflective of a broader pattern observed in many manufacturing sectors across Nigeria, where early adoption of green practices has not transitioned into fully integrated sustainability strategies. For instance, some larger firms in Nnewi have made strides in adopting solar energy technology, acknowledging both its environmental benefits and the long-term cost savings associated with reduced dependence on fossil fuels. However, despite these advancements, many companies lack a structured framework guiding their overall sustainability goals (Umar et al., 2021). This lack of a comprehensive approach means that any benefits derived from isolated energy-saving initiatives may not contribute to substantial improvements in operational sustainability or environmental performance.

Furthermore, SMEs within these industrial clusters exhibit a more conservative approach to green practices. Many are limited by financial constraints and a lack of awareness regarding the long-term advantages of adopting comprehensive green frameworks. Anecdotal evidence suggests that a significant number of these small firms still rely on outdated machinery, which not only increases operational costs but also decreases overall efficiency in energy consumption (Afum et al., 2020). As a result, the potential for sustainable practices to enhance their productivity and reduce environmental impact remains largely untapped. In addition to financial barriers, the absence of a robust policy framework that promotes environmental sustainability further complicates matters. Existing regulatory policies often lack clear guidelines on green practices, and the enforcement mechanisms necessary to ensure compliance are weak (Chidiebube et al., 2025). This results in a situation where firms are not sufficiently motivated to shift towards sustainable operational practices, especially when immediate economic pressures take precedence over long-term environmental considerations.

Furthermore, the implementation of green manufacturing processes is often stymied by inadequate access to training and resources that could facilitate such transitions. Thus, while some firms in Nnewi are making modest steps towards energy efficiency, the overall evidence suggests a fragmented approach rather than a coordinated movement towards comprehensive sustainability frameworks. Addressing the lack of comprehensive green practices in Anambra's industrial clusters requires concerted efforts from both the government and industry leaders. Initiatives should focus on creating awareness, providing financial and technical support, and establishing policies that incentivize the adoption of sustainable practices. As highlighted by recent literature, the success of green manufacturing strategies relies not only on individual initiatives but also on integrating advanced operations

management principles such as Total Quality Management (TQM) and Just-in-Time (JIT) that support comprehensive sustainability (Nwaulune, 2024).

Drivers and Incentives for Green Transition

The transition to green manufacturing practices in Anambra State is driven by several factors that compel local industries, particularly SMEs and larger firms, to adopt more sustainable practices. Key drivers include the rising costs of diesel, export market demands for eco-compliance, pressure from non-governmental organizations (NGOs) and environmental groups, and technological spillovers from multinational corporations.

1. **Rising Cost of Diesel Encourages Alternative Energy Use:** The escalating prices of diesel fuel have prompted many manufacturing firms in Anambra to seek alternative energy sources. For industries reliant on fossil fuel generators, increased operational costs can prompt a re-evaluation of energy strategies. Firms are increasingly investing in renewable energy solutions, such as solar panels, to mitigate fuel costs and promote sustainability. Research indicates that rising fossil fuel prices often push companies toward the adoption of cleaner energy alternatives, ultimately leading to improved energy efficiency and reduced emissions (Singh et al., 2021).
2. **Export Market Demands Eco-Compliance:** Many firms in Anambra that engage in international trade face increasing pressure to comply with global environmental standards. Export markets increasingly prioritize eco-compliance, requiring suppliers to demonstrate their commitment to sustainable practices. This demand for adherence to environmental regulations not only enhances the reputation of these firms but also provides them with market advantages. Studies have shown that companies that embrace green production methods are often better positioned to compete in environmentally conscious markets (Baah et al., 2020). This has led to a more systematic adoption of green practices among exporters as they seek to maintain their market positions and avoid potential sanctions.
3. **Pressure from NGOs and Environmental Groups:** Non-governmental organizations and environmental activist groups play a significant role in promoting environmental awareness and accountability among industries. In Anambra, these organizations create awareness about the importance of sustainable practices and hold businesses accountable for their environmental impacts. The pressure exerted by these stakeholders often prompts manufacturers to adopt greener technologies and practices to improve their public image and align with societal expectations. Research highlights that stakeholder pressures can serve as a catalyst for green innovation, particularly in response to community and environmental advocacy (Okpala et al., 2025).
4. **Technological Spillovers from Multinationals:** The presence of multinational corporations (MNCs) in Nigeria brings with it an opportunity for local firms to benefit from technological spillovers. These foreign companies often implement advanced green technologies and practices that, when observed by local counterparts, can spur innovation and the adoption of similar measures. Knowledge transfer through partnerships, collaborations, or direct interactions enables SMEs and local manufacturers to adopt environmentally friendly practices with greater ease. Evidence indicates that collaboration with MNCs can provide SMEs access to the latest

technologies and best practices, facilitating a smoother transition to sustainable operations (Baah et al., 2020).

The adoption of green manufacturing practices in Anambra State is influenced by multiple factors, including economic pressures from rising diesel costs, market demands for eco-compliance, advocacy from NGOs, and the positive impact of technological spillovers from multinational companies. These drivers not only encourage local industries to adopt sustainable practices but also highlight the need for a supportive policy environment to facilitate and reinforce these efforts. As companies leverage these drivers, the potential for substantial improvements in environmental performance and overall sustainability within Anambra's industrial landscape increases.

Challenges and Barriers to Implementation

The transition to green manufacturing practices in Anambra State, Nigeria, is hindered by various challenges and barriers that impede the effective implementation of sustainable initiatives. Understanding these barriers is crucial for devising strategies to facilitate the adoption of green practices within local industries.

1. **High Upfront Cost of Green Technologies:** One of the most significant challenges facing industries, especially SMEs, is the high initial cost associated with adopting green technologies. These investments often include the purchase of energy-efficient machinery, solar panels, and other renewable energy solutions. Many SMEs in Anambra operate under tight budgets, making it difficult to allocate sufficient funds for such capital-intensive upgrades. The perceived financial risk of transitioning to green technologies discourages firms from making the necessary investments, thereby stalling progress toward sustainability.
2. **Lack of Technical Know-How:** Another substantial barrier is the lack of technical expertise needed for the implementation and maintenance of green technologies. Many local firms do not have access to the necessary training or resources required to develop the skills essential for adopting and managing new technologies. This knowledge gap can lead to ineffective implementation of green solutions and diminished returns on investment. Capacity-building programs focusing on technical training and support are crucial for empowering local industries and fostering the adoption of green practices.
3. **Poor Policy Enforcement:** Despite the existence of environmental regulations, such as the NESREA Act, enforcement remains weak at the state level. This lack of enforcement allows industries to continue unsustainable practices without facing significant consequences. As a result, firms may lack the motivation to adopt greener practices, as compliance with environmental standards is not strictly monitored.
4. **Inadequate Government Incentives:** The absence of government incentives further complicates the adoption of green manufacturing practices. In many cases, local industries do not receive adequate support in the form of subsidies, tax breaks, or grants to encourage the implementation of environmentally friendly technologies. Without these incentives, the economic benefits of adopting green practices may not be compelling enough to overcome the initial financial hurdles.
5. **Limited Awareness of Long-Term Benefits:** Many local business owners and managers may lack awareness of the long-term benefits associated with adopting green

manufacturing practices. This includes not only potential cost savings from energy efficiency and waste reduction but also the reputational advantages of being seen as a socially and environmentally responsible business. Increasing awareness through workshops, seminars, and collaboration with environmental organizations could help educate stakeholders about the importance of sustainability and the overarching benefits of a green transition.

The challenges and barriers hindering the adoption of green manufacturing practices in Anambra State are multifaceted, involving economic, technical, regulatory, and awareness-related aspects. A coordinated approach that encompasses financial support, technical training, strict enforcement of environmental regulations, and enhanced awareness campaigns will be vital in overcoming these barriers and facilitating the transition to greener manufacturing practices. Addressing these challenges is essential for promoting sustainable industrial development in Anambra, thereby aligning local industries with global sustainability trends.

5. Impact on Sustainable Industrial Development

Environmental Impact

The adoption of green manufacturing practices in Anambra State has significant positive implications for the environment, particularly in terms of reducing greenhouse gas emissions and enhancing material efficiency within local industries. This section discusses two critical aspects of the environmental impact: the reduction in greenhouse gas emissions through the use of solar energy and the reduction of scrap material waste by 15-20% achieved through process improvements.

1. **Reduction in Greenhouse Gas Emissions:** The shift towards renewable energy sources, especially solar power, has notable implications for reducing greenhouse gas emissions (GHGs) in Anambra's manufacturing sectors. As firms increasingly install solar panels to meet their energy needs, the reliance on fossil fuels diminishes significantly. While the specific estimate of a 58% reduction in GHGs is not universally applicable to all contexts, studies generally indicate that transitioning to solar energy contributes substantially to CO₂ emissions reduction (Malik et al., 2020). The reduction in GHGs not only contributes to improved air quality but also plays a crucial role in combating climate change effects that disproportionately impact developing regions like Anambra State.
2. **Reduction of Scrap Material Waste:** Evidence from industrial clusters in Nnewi suggests that local firms have successfully reduced scrap material waste by 15-20% through enhanced production processes and better waste management strategies. This improvement is often a result of adopting lean manufacturing principles, which emphasize waste reduction and efficient resource utilization (Afum et al., 2020). By optimizing processes, manufacturers can effectively convert what was previously considered waste into valuable rework or recycling opportunities. Such practices not only lower operational costs but also improve overall environmental sustainability by minimizing resource depletion and reducing the volume of waste sent to landfills.

The positive impacts of adopting green practices, including the reduction of GHG emissions and waste, underscore the potential for these practices to contribute to sustainable industrial development in Anambra State. The adoption of advanced technologies and

innovative methodologies plays a pivotal role in achieving these environmental benefits. Exploring the economic dimensions of these transitions is equally important, as firms that reduce waste and GHG emissions often experience enhanced profitability and competitiveness in both local and international markets (Oláh et al., 2020). While significant progress has been made in reducing environmental impacts through green manufacturing practices in Anambra, further collaboration among stakeholders—including governmental bodies, NGOs, and the private sector—is essential. Establishing robust policy frameworks and financial incentives can accelerate the adoption of renewable energy solutions and waste reduction practices, enhancing the overall sustainability of industrial activities in the region.

Economic Impact

The adoption of green manufacturing practices in Anambra State is poised to create significant economic benefits for local industries. This section discusses three key economic impacts: energy cost savings through leaner operations, the emergence of new opportunities in green product markets, and the competitive advantages for firms that achieve export compliance.

1. **Energy Cost Savings Through Leaner Operations:** One of the primary benefits of implementing green manufacturing practices is the reduction in energy costs. By adopting leaner operations, firms can optimize their processes to improve efficiency and minimize waste. Studies have shown that companies that reinforce energy management and implement energy-efficient technologies often realize substantial cost savings. For instance, recent research indicates that energy cost reductions not only enhance operational profitability but also contribute to lower greenhouse gas emissions, thereby reinforcing the business case for green manufacturing (Umar et al., 2021). In Anambra, local firms that invest in energy-efficient machinery or incorporate renewable energy sources like solar power see a direct financial return on these investments, enabling them to direct savings toward further innovations or improvements.
2. **New Opportunities in Green Product Markets:** As global consumer awareness regarding environmental sustainability continues to grow, demand for green products is rising. This trend presents Anambra's manufacturers with opportunities to develop and market eco-friendly products. By positioning themselves to meet these demands, firms can tap into expanding markets both locally and internationally. Green innovations, such as biodegradable packaging and eco-friendly textiles, are increasingly sought after by consumers who are willing to pay a premium for products that align with their values (Khan et al., 2023). This shift not only opens new revenue streams but also encourages firms to invest in research and development, leading to further innovation and competitiveness.
3. **Competitive Advantage for Export-Compliant Firms:** Manufacturers in Anambra that comply with international environmental standards gain a competitive edge, particularly in export markets. Many international buyers are now setting sustainability criteria as prerequisites for partnership, compelling local firms to adopt green practices (Yacob et al., 2019). Firms that can demonstrate their commitment to environmental stewardship may benefit from enhanced reputations, better access to global supply chains, and increased customer loyalty. For example, export-compliant companies not only avoid potential penalties associated with non-compliance but also enjoy preferential

treatment in international trade agreements, giving them a strategic advantage in saturated markets. Research emphasizes that operational competitiveness and firm reputation are significantly enhanced when companies adopt green manufacturing practices, supporting the case for sustainability-focused strategies (Afum et al., 2020).

The economic impacts of adopting green manufacturing practices in Anambra State are multifaceted and promising. From significant energy cost savings to accessing new markets for green products and achieving competitive advantages in export markets, the transition to more sustainable manufacturing approaches presents tangible benefits. As local firms embrace these practices, it is crucial that they receive sufficient support through government policies and incentives designed to facilitate their green transitions, further reinforcing the positive economic narratives associated with sustainability.

Social Impact

The integration of green manufacturing practices in Anambra State, Nigeria, yields significant social benefits, notably in worker health and the creation of new employment opportunities. This section explores two critical facets of the social impact of green practices: improved worker health resulting from cleaner workplaces and the creation of green jobs in sectors such as waste management, renewable energy, and environmental consulting.

1. **Improved Worker Health from Cleaner Workplaces:** Transitioning to greener manufacturing environments positively impacts worker health by reducing exposure to harmful substances and improving overall workplace conditions. Cleaner production processes often involve minimizing or eliminating toxic materials, which are common in traditional manufacturing settings. Research indicates that greener workplace environments contribute to lower incidences of occupational health issues, such as respiratory problems and chronic diseases linked to exposure to hazardous materials. In Anambra, firms that adopt environmentally friendly practices, including proper waste management and non-toxic materials, are likely to report fewer health-related incidents and improved worker satisfaction. Enhanced workplace health contributes to employee well-being, promotes productivity, and fosters a more committed workforce.
2. **Creation of Green Jobs:** The shift toward green manufacturing also catalyses the creation of green jobs, particularly in sectors related to waste management, renewable energy, and environmental consulting. As industries adopt sustainable practices, there is an increasing demand for skilled professionals to manage these initiatives. For instance, careers in waste management have expanded as firms seek to develop efficient, eco-friendly waste disposal systems, which are essential for compliance with evolving environmental regulations. Additionally, the push for renewable energy solutions has opened up employment opportunities in the installation and maintenance of renewable energy systems, contributing to local economic development. Furthermore, consultancy roles have proliferated as firms seek guidance on implementing green practices and navigating regulatory requirements. Green consultants play a crucial role in advising SMEs in Anambra on best practices for sustainability, conducting environmental audits, and helping organizations achieve eco-certifications. The rise of these positions represents a transformative shift in the labour market, positioning Anambra as a potential leader in green jobs within Nigeria.

The adoption of green manufacturing practices in Anambra State presents substantial social benefits, including improved worker health and the creation of new job opportunities in emerging sectors. As these green practices become more prevalent, the positive impact on the workforce will contribute to sustainable industrial development in the region, aligning economic growth with environmental responsibility. To maximize these social benefits, stakeholders must continue to support initiatives that facilitate the adoption of green technologies and practices, ensuring that local industries remain competitive and responsive to the changing global landscape.

Alignment with SDGs and Nigeria’s Climate Goals

Green manufacturing plays a crucial role in aligning industrial practices with the United Nations Sustainable Development Goals (SDGs), particularly Goals 9 (Industry, Innovation, and Infrastructure), 12 (Responsible Consumption and Production), and 13 (Climate Action). In the context of Nigeria, these practices align with the country’s Nationally Determined Contributions (NDCs) under the Paris Agreement, which emphasizes sustainable industrial processes that mitigate climate change impacts. Implementation of green manufacturing can enhance innovation and efficiency within industries, which is vital for achieving sustainable industrial growth in Anambra State, Nigeria (Nwokolo et al., 2023; Kehinde et al., 2024). By integrating green technologies and practices, Nigerian industries can improve their operational efficiency and contribute to significant reductions in greenhouse gas emissions, thus advancing Nigeria's climate goals (Kehinde et al., 2024; Richard et al., 2021). Furthermore, the transition to green manufacturing can bolster local economies through the creation of green jobs and sustainable business practices, fostering long-term economic resilience (Richard et al., 2021; Nwamekwe et al., 2024). This proactive stance on sustainability directly connects with global climate initiatives, reinforcing Nigeria's commitment to addressing climate change through responsible manufacturing practices (Nwokolo et al., 2023; Kehinde et al., 2024; Onuoha & Okoye, 2020).

Ky Hubs, Sectors-and Challenges



Figure 3: A Chart of The Industrial Landscape of Anambra State

6. Strategic Role of Industrial Engineers

Process Optimization and Eco-efficiency

Industrial engineers are pivotal in the adoption of green manufacturing practices, primarily through process optimization and eco-efficiency strategies. By redesigning production lines for energy efficiency, they enhance overall operational performance and reduce environmental impacts (Afum et al., 2020; Umar et al., 2021). The integration of simulation tools and methodologies like Six Sigma allows these engineers to analyse workflows meticulously, leading to optimized material usage and significant waste minimization (Gholami et al., 2024). The deployment of Six Sigma principles helps in identifying inefficiencies in production processes, thereby fostering eco-efficient practices that contribute to both economic and environmental sustainability (Khan et al., 2023). Moreover, as manufacturing technologies evolve under Industry 4.0, the role of industrial engineers becomes increasingly critical. They are tasked with integrating emerging technologies to enhance operational capacity while maintaining environmental stewardship (Ezeanyim et al., 2025). Research indicates that such improvements can lead to better compliance with regulatory standards and increased competitiveness in the market (Igbokwe et al., 2025). By merging green practices with lean manufacturing principles, industrial engineers can significantly reduce resource consumption and enhance the sustainable performance of manufacturing firms (Umar et al., 2021; Gholami et al., 2024).

Lean-Green Integration in Production

The integration of lean manufacturing—focused on waste elimination—with green manufacturing—aimed at enhancing eco-efficiency—fosters significant dual benefits in productivity and environmental performance, particularly for resource-constrained SMEs. By combining these methodologies, industrial engineers can optimize production processes, maximize resource utilization, and minimize waste (Tripathi et al., 2021; Cherrafi et al., 2019; Vasconcelos et al., 2019). This efficiency not only lowers operational costs but also enhances environmental sustainability, positioning SMEs competitively in the market amidst increasing regulatory pressures for greener practices (Cherrafi et al., 2019; Vasconcelos et al., 2019). Moreover, integrating lean and green principles cultivates a culture of continuous improvement and innovation within manufacturing firms. This approach, often associated with the Kaizen philosophy, allows organizations to systematically identify inefficiencies and waste, leading to enhanced operational performance and resource conservation (Cherrafi et al., 2019; Vasconcelos et al., 2019). Studies suggest that the adoption of a lean-green framework can enable SMEs in Nigeria, particularly Anambra State, to navigate financial constraints effectively while contributing positively to local sustainability goals (Cherrafi et al., 2019). Such integration underscores the strategic role of industrial engineers in promoting sustainable practices that align economic viability with environmental responsibility in manufacturing (Tripathi et al., 2021; Cherrafi et al., 2019).

Opportunities for Digital Tools and Automation

The strategic role of industrial engineers in the adoption of green manufacturing practices is greatly enhanced through the utilization of digital tools and automation. By employing smart meters, sensors, and predictive analytics, these engineers can effectively track resource usage and facilitate real-time decision-making that supports sustainability

goals. The integration of such technologies allows for improved monitoring of energy consumption and material flows, leading to more efficient operational processes (Afum et al., 2020). Recent studies highlight that digital tools enable manufacturing firms to optimize their production systems, significantly reducing waste and energy consumption. This digital transformation bolsters productivity and enhances eco-efficiency within the manufacturing sector (Yacob et al., 2019). Industrial engineers are well-positioned to lead these innovations, leveraging their expertise in systems design and process improvement to implement effective green strategies. The data generated from these tools can be analysed to identify trends and forecast resource needs, further promoting sustainable practices within firms (Afum et al., 2020; Yacob et al., 2019). Moreover, the application of digital solutions is particularly advantageous for SMEs in resource-constrained environments. By integrating these technologies, SMEs can improve their operational capabilities and compete more effectively in broader markets while adhering to environmental sustainability standards (Wang et al., 2022). Ultimately, the leadership of industrial engineers in adopting automation and digital tools catalyses a transformative shift towards more sustainable manufacturing processes (Yacob et al., 2019).



Figure. 4: The Role of Industrial Engineers in Green Transition

7. Recommendations and Future Directions

Policy and Institutional Support Needs

In order to enhance the adoption of green manufacturing practices and contribute to sustainable industrial development in Anambra State, several recommendations for policy and institutional support are imperative. These recommendations focus on establishing regulatory frameworks, financial incentives, and certification programs that can effectively promote sustainability within the manufacturing sector.

1. **Enforce State-Level Green Industrial Standards:** The establishment and enforcement of state-level green industrial standards are critical for promoting sustainable manufacturing in Anambra. Current policies, including national standards, may lack focused implementation at the state level. Enforcing stricter regulations that align with environmental sustainability objectives can ensure compliance among local industries. Such standards should include emission limits, waste management protocols, and

energy efficiency benchmarks. Drawing from successful examples in other regions, as highlighted in Aditiyawan et al., governments can benefit from implementing consistent certification processes that hold industries accountable for their environmental footprints. These standards can create a level playing field, encouraging all firms to adopt greener practices to meet legal requirements (Aditiyawan et al., 2023).

2. **Provide Tax Incentives or Subsidies for Eco-Friendly Equipment:** Financial constraints are a significant barrier to the adoption of green technologies, particularly for SMEs. An effective strategy to promote green manufacturing is the introduction of tax incentives or subsidies for companies investing in eco-friendly equipment and renewable energy installations. These financial incentives can help mitigate the high upfront costs associated with transitioning to green technologies, encouraging firms to invest in sustainability. Although the reference (Chan et al., 2018) focuses primarily on barriers specific to green building technologies in a different context, the identified barriers such as lack of incentives can be analogously applied to green manufacturing technologies in Anambra. Similar programs have proven beneficial in promoting green practices in other contexts by alleviating budget constraints and stimulating investments in energy-efficient technologies.
3. **Create Certification Programs for Green-Compliant Firms:** Establishing certification programs for firms that meet specific green criteria can serve as a powerful motivator for local industries to adopt sustainable practices. Such programs, akin to those implemented in various sectors globally, could grant official recognition to businesses that demonstrate eco-friendly practices. These certifications would not only enhance a company's reputation but also improve its marketability, as consumers increasingly favour environmentally responsible products. The implementation of green industry certification, as shown in case studies from Indonesia, highlights that such initiatives can promote eco-friendly industries and foster a culture of sustainability within Anambra's manufacturing landscape (Aditiyawan et al., 2023; Nwamekwe et al., 2024). Furthermore, these certifications can be tied to government incentives, creating a holistic approach that encourages compliance and environmental responsibility.

The effectiveness of green manufacturing in Anambra State can be significantly enhanced through robust policy and institutional support. Enforcing green industrial standards, providing financial incentives for eco-friendly equipment, and establishing certification programs are critical steps toward fostering a culture of sustainability within local industries. Aligning these efforts with community engagement and industry collaboration will yield substantial long-term benefits for environmental performance and sustainable economic growth. By enhancing the policy landscape, Anambra can position itself as a leader in green manufacturing practices within Nigeria, contributing positively to local and global sustainability frameworks.

Capacity Building and Awareness

To enhance the adoption of green manufacturing practices in Anambra State, particularly among SMEs, it is critical to focus on capacity building and raising awareness. This can be achieved through targeted training programs, educational reforms in engineering curricula, and workshops organized by local chambers of commerce. These initiatives can

foster a culture of sustainability within the industrial landscape of Anambra, ensuring that industries are better equipped to transition to environmentally friendly practices.

1. **Training Programs for SMEs on Energy Efficiency:** Implementing comprehensive training programs focused on energy efficiency specifically tailored for SMEs can significantly enhance their operational practices. These programs should cover best practices in energy management, waste reduction strategies, and the integration of renewable energy technologies. By educating business owners and staff on how to optimize resource use, minimize wastage, and implement energy-efficient solutions, SMEs can not only lower their operational costs but also contribute to environmental sustainability. Research indicates that education and capacity building are essential to overcoming barriers to adopting sustainable practices (Ullah et al., 2024). Additionally, partnering with technical institutions and sustainability experts can provide SMEs with the necessary support to instil best practices in their operations.
2. **Inclusion of Sustainability Modules in Engineering Curricula:** Incorporating sustainability education into engineering programs at universities and technical colleges in Anambra is critical for fostering a future workforce that is well-versed in green manufacturing principles. By including modules focused on sustainable design, renewable energy technologies, and lifecycle assessment in engineering curricula, educational institutions can equip students with the knowledge and skills needed to pursue environmentally friendly practices in their future careers. Integrating such modules not only raises awareness among students but also encourages innovative thinking around sustainability challenges that they will face in the professional realm (Nwamekwe et al., 2025).
3. **Workshops by Local Chambers of Commerce:** Local chambers of commerce play a vital role in facilitating networking and collaboration among businesses. By organizing workshops focused on green manufacturing, these chambers can raise awareness about sustainability challenges and opportunities. Workshops could feature expert speakers on sustainability topics, case studies of successful green initiatives, and collaborative sessions to develop actionable strategies for implementing eco-friendly practices. Furthermore, these forums can serve as platforms for sharing resources and best practices, thereby creating a community of businesses committed to sustainability. Studies indicate that collaborative practices and stakeholder engagement significantly enhance awareness and commitment to sustainability initiatives (Bektaş et al., 2024).

Capacity building and awareness-raising initiatives are essential to promote green manufacturing practices in Anambra State. By implementing targeted training programs for SMEs, embedding sustainability in engineering education, and facilitating workshops through local chambers of commerce, the region can foster a cultural shift towards sustainability. These efforts will not only enhance the competitiveness of local firms but also contribute to broader environmental and social goals, paving the way for sustainable industrial development in Anambra State.

Research and Innovation Priorities in Green Tech

To facilitate the widespread adoption of green manufacturing practices in Anambra State, specific research and innovation priorities must be established. Focusing on the development of solar-powered industrial systems, circular economy models for metal and

plastic waste, and locally adaptable eco-friendly production technologies will not only enhance sustainability but also stimulate economic growth within the region.

1. **Solar-Powered Industrial Systems:** Investing in research and development for solar-powered industrial systems presents a promising opportunity for Anambra's manufacturing sector. Given the rising costs of traditional energy sources, transitioning to solar energy can lead to significant cost savings while simultaneously reducing greenhouse gas emissions (Cherrafi et al., 2018). Research should focus on developing scalable solar technologies that are tailored to local industrial needs, assessing both feasibility and potential return on investment. The deployment of solar technologies can also encourage the establishment of small solar energy firms, further diversify the local economy and foster energy independence. Moreover, collaborative efforts with academic institutions and renewable energy organizations can help drive innovation and knowledge transfer in solar technology applications (Malik et al., 2020).
2. **Circular Economy Models for Metal and Plastic Waste:** Transitioning towards a circular economy framework is essential for managing waste effectively in Anambra's industrial landscape. Research should prioritize the development of comprehensive models that facilitate the recycling and repurposing of metal and plastic waste generated by local industries. Existing studies indicate that implementing circular economy principles can significantly reduce raw material consumption and environmental pollution (Afum et al., 2020). Developing partnerships with educational institutions, recycling firms, and government agencies can create collaborative platforms for sharing best practices in waste management and recycling processes. Furthermore, pilot projects that demonstrate the economic benefits of circular economy models will provide empirical evidence and serve as potential case studies for broader adoption.
3. **Locally Adaptable Eco-Friendly Production Technologies:** To ensure that green technologies are accessible to local firms, research should focus on developing eco-friendly production technologies that are adaptable to the specific context of Anambra. This includes designing affordable and efficient manufacturing processes that utilize locally sourced materials and labour. Such innovations can mitigate the financial barriers that prevent SMEs from adopting green practices (Nwamekwe and Okpala, 2025). Innovations could draw from traditional practices and materials that align with modern sustainability standards, ensuring that they are both culturally relevant and economically viable. Additionally, training and capacity-building initiatives must accompany these technological advancements to ensure that local firms can effectively integrate new eco-friendly practices into their operations.

Prioritizing research and innovation in these key areas can significantly advance the sustainability agenda for Anambra State's manufacturing sector. Enhanced collaboration between government, industry, and academic institutions will be critical in fostering an environment conducive to innovation and the effective implementation of green manufacturing practices. By focusing on solar energy systems, circular economy models, and locally adapted technologies, Anambra can pave the way for sustainable industrial development that supports both environmental initiatives and economic growth.

CONCLUSION

Summary of Key Findings

This study has demonstrated that green manufacturing practices in Anambra State remain at an early stage of adoption, with implementation largely confined to a few large firms, while most SMEs continue to rely on outdated technologies, fossil-fuel generators, and unsustainable waste management practices. These limitations are driven by high upfront costs of green technologies, technical capacity gaps, weak policy enforcement, and insufficient awareness of long-term benefits.

Despite these barriers, the research highlights that green manufacturing offers substantial benefits across environmental, economic, and social dimensions. Environmentally, firms incorporating solar energy, energy-efficient machinery, and lean production techniques achieved reductions in greenhouse gas emissions and material waste by up to 15–20%, fostering climate change mitigation and resource efficiency. Economically, these firms realized significant energy cost savings, access to emerging eco-conscious markets, and enhanced export competitiveness due to compliance with international standards. Socially, the transition facilitated improved worker health through cleaner production processes and the creation of green jobs in renewable energy, waste management, and environmental consulting. These findings collectively affirm that green manufacturing not only advances environmental stewardship but also strengthens industrial resilience and socio-economic growth in Anambra State.

Implications for Stakeholders

The findings hold critical implications for key stakeholders seeking to accelerate sustainable industrial development in the region. Policymakers must strengthen the regulatory landscape by enforcing state-specific green industrial standards, offering tax incentives and subsidies, and establishing certification programs to reduce the financial burden on firms, particularly SMEs.

Industrial engineers occupy a central role as change agents, leveraging lean-green integration, process optimization, and digital tools such as smart meters, sensors, and predictive analytics to enhance eco-efficiency and minimize waste.

Industry leaders and SMEs must view sustainability as a strategic lever for innovation, competitiveness, and profitability, rather than a compliance-driven burden, by investing in energy-efficient equipment and circular economy systems. Academic institutions and training bodies should embed sustainability-focused modules and technical training into engineering curricula and workforce programs to address skills gaps.

NGOs and environmental advocacy groups must continue to drive awareness, foster transparency, and facilitate collaboration between industries and government agencies to sustain momentum toward a green transition. Collaborative engagement across these stakeholder groups is essential to overcome the entrenched financial, technical, and policy-related barriers that currently hinder widespread adoption of green manufacturing practices in Anambra.

Final Thoughts on Sustainability in Anambra's Industry

Anambra State stands at a transformative juncture in its industrial trajectory, with the potential to evolve from resource-intensive, traditional manufacturing toward becoming a regional model for sustainable industrial development. While current adoption remains

fragmented, the rising cost of diesel, export market pressures for eco-compliance, technological spillovers from multinationals, and growing public demand for environmentally responsible products present strong drivers for change.

Sustainability in Anambra's industry will ultimately depend on the alignment of three critical enablers:

1. Robust policy and institutional frameworks that reduce investment risks through clear standards and incentives,
2. Capacity-building initiatives and technical training to empower industrial engineers, entrepreneurs, and SMEs, and
3. Locally adaptable technological innovations, including renewable energy systems, circular economy models, and cost-effective eco-friendly production technologies.

If these enablers are strategically deployed, Anambra can position itself as a benchmark for sustainable manufacturing in Nigeria, aligning industrial growth with the United Nations Sustainable Development Goals (SDGs), particularly Goals 9, 12, and 13 and advancing Nigeria's commitments under the Paris Agreement and Nationally Determined Contributions (NDCs). Through coordinated stakeholder action and innovative industrial strategies, the state can achieve a balanced pathway of economic expansion, environmental stewardship, and social development, securing its place as a competitive and sustainable industrial hub in West Africa.

Conflict of Interest Statement

There is no conflict of interest with any person / institution in the article prepared.

REFERENCES

- Adamik, A. and Sikora-Fernandez, D. (2021). Smart organizations as a source of competitiveness and sustainable development in the age of industry 4.0: integration of micro and macro perspective. *Energies*, 14(6), 1572. <https://doi.org/10.3390/en14061572>
- Afum, E., Osei-Ahenkan, V., Agyabeng-Mensah, Y., Owusu, J., Kusi, L., & Ankomah, J. (2020). Green manufacturing practices and sustainable performance among Ghanaian manufacturing SMEs: the explanatory link of green supply chain integration. *Management of Environmental Quality an International Journal*, 31(6), 1457-1475. <https://doi.org/10.1108/meq-01-2020-0019>
- Ardiana, N., Suryawan, I., Ridhosari, B., & Sari, M. (2022). Hazardous waste generation and composition from electric train activities. *Ijca (Indonesian Journal of Chemical Analysis)*, 5(1), 62-67. <https://doi.org/10.20885/ijca.vol5.iss1.art7>
- Arinaitwe, A., Tukamuhabwa, B., Bagire, V., Nkurunziza, G., & Nassuna, A. (2024). Nudging manufacturing small and medium enterprises in developing communities to energy management: exploring the role of institutional pressure dimensions. *Journal of Enterprising Communities People and Places in the Global Economy*, 18(6), 1337-1363. <https://doi.org/10.1108/jec-05-2023-0083>
- Baah, C., Jin, Z., & Tang, L. (2020). Organizational and regulatory stakeholder pressures friends or foes to green logistics practices and financial performance: investigating corporate reputation as a missing link. *Journal of Cleaner Production*, 247, 119125. <https://doi.org/10.1016/j.jclepro.2019.119125>

- Barik, S. and Mondal, M. (2025). Effect of active substrate cooling in wire arc additive manufacturing for manganese-rich low-carbon steel. *Materialwissenschaft Und Werkstofftechnik*, 56(3), 364-375. <https://doi.org/10.1002/mawe.202400099>
- Bektaş, Y., Güçlü, Ç., & Meço, B. (2024). Evaluation of operating room staff awareness of environmental sustainability and medical waste management. *Turkish Journal of Anaesthesiology and Reanimation*, 142-146. <https://doi.org/10.4274/tjar.2024.231490>
- Bianchi, P., Labory, S., & Tomlinson, P. (2023). Shaping sustainable industrial development paths., 2-16. <https://doi.org/10.4337/9781800379091.00008>
- Borha, D. and Olujobi, O. (2023). An examination of the petroleum industry act 2021: prospects, challenges, and the way forward. *F1000research*, 12, 551. <https://doi.org/10.12688/f1000research.132539.2>
- Borland, H., Bhatti, Y., & Lindgreen, A. (2019). Sustainability and sustainable development strategies in the U.K. plastic electronics industry. *Corporate Social Responsibility and Environmental Management*, 26(4), 805-818. <https://doi.org/10.1002/csr.1722>
- Caldera, S., Desha, C., & Dawes, L. (2019). Evaluating the enablers and barriers for successful implementation of sustainable business practice in 'lean' SMEs. *Journal of Cleaner Production*, 218, 575-590. <https://doi.org/10.1016/j.jclepro.2019.01.239>
- Chan, A., Darko, A., Olanipekun, A., & Ameyaw, E. (2018). Critical barriers to green building technologies adoption in developing countries: the case of Ghana. *Journal of Cleaner Production*, 172, 1067-1079. <https://doi.org/10.1016/j.jclepro.2017.10.235>
- Cherrafi, A., Elfezazi, S., Hurley, B., Garza-Reyes, J., Kumar, V., Anosike, A., ... & Batista, L. (2019). Green and lean: a Gemba-kaizen model for sustainability enhancement. *Production Planning & Control*, 30(5-6), 385-399. <https://doi.org/10.1080/09537287.2018.1501808>
- Chidiebube, I. N., Onyeka, N. C., Sunday, A. P., & Chiedu, E. O. (2025). A Comparative Analysis of Machine Learning Models for Inventory Demand Forecasting in A Food Manufacturing Sme. *Indonesian Journal of Innovation Science and Knowledge*, 2(3), 35-48. Retrieved from <https://knowledge.web.id/index.php/ijisk/article/view/177>
- D'Angelo, V., Cappa, F., & Peruffo, E. (2022). Green manufacturing for sustainable development: the positive effects of green activities, green investments, and non-green products on economic performance. *Business Strategy and the Environment*, 32(4), 1900-1913. <https://doi.org/10.1002/bse.3226>
- Ekesiobi, C. and Dimnwobi, S. (2020). Economic assessment of the Igbo entrepreneurship model for entrepreneurial development in Nigeria: evidence from clusters in Anambra state. *International Journal of Entrepreneurial Behaviour & Research*, 27(2), 416-433. <https://doi.org/10.1108/ijebr-11-2019-0640>
- Ezeanyim, O. C., Ewuzie, N. V., Aguh, P. S., Nwabueze, C. V., and Nwamekwe, C. O. (2025). Effective Maintenance of Industrial 5-Stage Compressor: A Machine Learning Approach. *Gazi University Journal of Science Part A: Engineering and Innovation*, 12(1), 96-118. <https://dergipark.org.tr/en/pub/gujisa/issue/90827/1646993>
- Foroughi, F., Ghomi, E., Dehaghi, F., Borayek, R., & Ramakrishna, S. (2021). A review on the life cycle assessment of cellulose: from properties to the potential of making it a low carbon material. *Materials*, 14(4), 714. <https://doi.org/10.3390/ma14040714>
- Frohn-Sörensen, P., Geueke, M., Tuli, T., Kuhnhen, C., Manns, M., & Engel, B. (2021). 3d printed prototyping tools for flexible sheet metal drawing. *The International Journal of*

- Advanced Manufacturing Technology, 115(7-8), 2623-2637.
<https://doi.org/10.1007/s00170-021-07312-y>
- Gholami, H., Lee, J., Garza-Reyes, J., & Salameh, A. (2024). Green lean six sigma practices: a scale development and measurement model from an engineer's perspective. *Journal of Manufacturing Technology Management*, 36(1), 179-202.
<https://doi.org/10.1108/jmtm-12-2023-0555>
- Habib, M., Bao, Y., Nabi, N., Dulal, M., Asha, A., & Islam, M. (2021). Impact of strategic orientations on the implementation of green supply chain management practices and sustainable firm performance. *Sustainability*, 13(1), 340.
<https://doi.org/10.3390/su13010340>
- Hejazi, M., Batati, B., & Bahurmuz, A. (2023). The influence of green supply chain management practices on corporate sustainability performance. *Sustainability*, 15(6), 5459. <https://doi.org/10.3390/su15065459>
- Igbokwe, N. C., Nwamekwe, C. O., Godwin, H. C., & Mba W. (2025). Optimization of Overall Equipment Effectiveness Factors in A Food Manufacturing Small and Medium Enterprise. *Journal of Research in Engineering and Applied Sciences (JREAS)*, 10(1), 836-845. <https://qtanalytics.in/journals/index.php/JREAS/article/view/4660>
- Igbokwe, N. C., Nwamekwe, C. O., Ono, C. G., Nwabunwanne, E. C., & Afunugo, P. S. A. (2024). The Role of Digital Twins in Optimizing Renewable Energy Utilization and Energy Efficiency in Manufacturing. *Siber International Journal of Digital Business (SIJDB)*, 1(4), 93–111. <https://doi.org/10.38035/sijdb.v1i4.262>
- Igbokwe, N. C., Okpala, C. C., & Nwamekwe, C. O. (2024). The Implementation of Internet of Things in the Manufacturing Industry: An Appraisal. *International Journal of Engineering Research and Development*, 20(7), 510-516. <https://www.ijerd.com/paper/vol20-issue7/2007510516.pdf>
- Jamal, T., Zahid, M., Martins, J., Mata, M., Rahman, H., & Mata, P. (2021). Perceived green human resource management practices and corporate sustainability: multigroup analysis and major industries perspectives. *Sustainability*, 13(6), 3045. <https://doi.org/10.3390/su13063045>
- Jianina, F. (2023). Environmental governance: challenges of environmentally friendly industrial areas in Dhaka city of Bangladesh. *International Journal Papier Advance and Scientific Review*, 4(4), 19-25. <https://doi.org/10.47667/ijpasr.v4i4.260>
- Jones, E., Vliet, M., Qadir, M., & Bierkens, M. (2021). Country-level and gridded estimates of wastewater production, collection, treatment and reuse. *Earth System Science Data*, 13(2), 237-254. <https://doi.org/10.5194/essd-13-237-2021>
- Kalyar, M., Shoukat, A., & Shafique, I. (2019). Enhancing firms' environmental performance and financial performance through green supply chain management practices and institutional pressures. *Sustainability Accounting Management and Policy Journal*, 11(2), 451-476. <https://doi.org/10.1108/sampj-02-2019-0047>
- Kehinde, T., Olanrewaju, F., Ezugwu, O., Rebecca, K., & Isaa, K. (2024). Navigating climate action in Nigeria: assessing sustainable development goal 13 implementation and challenges. *Journal of Law and Sustainable Development*, 12(1), e971. <https://doi.org/10.55908/sdgs.v12i1.971>
- Khan, M., Idrees, M., & Haider, Y. (2023). Industry 4.0 impacts on operational and green innovation performances with the mediation of green practices. *International Journal of*

- Productivity and Performance Management, 73(5), 1405-1426.
<https://doi.org/10.1108/ijppm-06-2022-0277>
- Kiswanto, G., Kholil, A., & Istiyanto, J. (2023). Effect of infill pattern on impact toughness, microstructure, and surface roughness of inconel 625 built via filament-based material extrusion additive manufacturing. *Journal of Manufacturing and Materials Processing*, 7(3), 114. <https://doi.org/10.3390/jmmp7030114>
- Luo, S., Yimamu, N., Li, Y., Wu, H., Irfan, M., & Hao, Y. (2022). Digitalization and sustainable development: how could digital economy development improve green innovation in China? *Business Strategy and the Environment*, 32(4), 1847-1871. <https://doi.org/10.1002/bse.3223>
- Malik, S., Cao, Y., Mughal, Y., Kundi, G., Mughal, M., & Ramayah, T. (2020). Pathways towards sustainability in organizations: empirical evidence on the role of green human resource management practices and green intellectual capital. *Sustainability*, 12(8), 3228. <https://doi.org/10.3390/su12083228>
- Mehta, J., Ahlawat, C., Tripathi, A., Chaudhary, V., & Gupta, P. (2025). Cleaner production techniques for developing sustainable polymeric composites: influencing factors, challenges and future applications. *Ecs Journal of Solid-State Science and Technology*, 14(4), 047001. <https://doi.org/10.1149/2162-8777/adc202>
- Nazir, S., Mehmood, S., Nazir, Z., & Li, Z. (2024). Linking manufacturing firms with environment: role of green manufacturing and environmental management on firm's environmental performance with moderating effect of external environmental regulations. *Journal of Manufacturing Technology Management*, 35(6), 1264-1291. <https://doi.org/10.1108/jmtm-10-2023-0442>
- Nwamekwe C. O., and Nwabunwanne E. C. (2025). Circular Economy and Zero-Energy Factories: A Synergistic Approach to Sustainable Manufacturing. *Journal of Research in Engineering and Applied Sciences (JREAS)*, 10(1), 829-835. <https://qtanalytics.in/journals/index.php/JREAS/article/view/4567>
- Nwamekwe C. O., Ewuzie Nnamdi Vitalis, Igbokwe Nkemakonam Chidiebube, & Nwabueze Chibuzo Victoria. (2025). Evaluating Advances in Machine Learning Algorithms for Predicting and Preventing Maternal and Foetal Mortality in Nigerian Healthcare: A Systematic Approach. (2025). *International Journal of Industrial and Production Engineering*, 3(1), 1-15. <https://journals.unizik.edu.ng/ijipe/article/view/5161>
- Nwamekwe C. O., Ezeanyim O. C., and Igbokwe N. C. (2025). Resilient Supply Chain Engineering in the Era of Disruption: An Appraisal. *International Journal of Innovative Engineering, Technology and Science (IJETS)*, 9(1), 11-23. <https://hal.science/hal-05061524/>
- Nwamekwe, C. O., and Igbokwe, N. C. (2024). Supply Chain Risk Management: Leveraging AI for Risk Identification, Mitigation, and Resilience Planning. *International Journal of Industrial Engineering, Technology & Operations Management*, 2(2), 41-51. <https://doi.org/10.62157/ijietom.v2i2.38>
- Nwamekwe, C. O., and Okpala, C. C. (2025). Circular economy strategies in industrial engineering: From theory to practice. *International Journal of Multidisciplinary Research and Growth Evaluation*, 6(1): 1773-1782. https://www.allmultidisciplinaryjournal.com/uploads/archives/20250212103754_MGE-2025-1-288.1.pdf

- Nwamekwe, C. O., and Okpala, C. C. (2025). Machine learning-augmented digital twin systems for predictive maintenance in highspeed rail networks. *International Journal of Multidisciplinary Research and Growth Evaluation*, 6(1), 1783-1795. https://www.allmultidisciplinaryjournal.com/uploads/archives/20250212104201_MGE-2025-1-306.1.pdf
- Nwamekwe, C. O., Chidiebube, I. N., Godfrey, O. C., Celestine, N. E., & Sunday, A. P. (2025). Resilience and Risk Management in Social Robot Systems: An Industrial Engineering Perspective. *Culture Education and technology research (Cetera)*, 2(2), 1–12. Retrieved from <https://cetera.web.id/index.php/ctr/article/view/154>
- Nwamekwe, C. O., Chinwuko, C. E. & Mgbemena, C. E. (2020). Development and Implementation of a Computerised Production Planning and Control System. *UNIZIK Journal of Engineering and Applied Sciences*, 17(1), 168-187
- Nwamekwe, C. O., Ewuzie, N. V., Igbokwe, N. C., Okpala, C. C., & U-Dominic, C. M. (2024). Sustainable Manufacturing Practices in Nigeria: Optimization and Implementation Appraisal. *Journal of Research in Engineering and Applied Sciences*, 9(3). <https://qtanalytics.in/journals/index.php/JREAS/article/view/3967>
- Nwamekwe, C. O., Ewuzie, N. V., Igbokwe, N. C., U-Dominic, C. M., & Nwabueze, C. V. (2024). Adoption of Smart Factories in Nigeria: Problems, Obstacles, Remedies and Opportunities. *International Journal of Industrial and Production Engineering*, 2(2). Retrieved from <https://journals.unizik.edu.ng/ijipe/article/view/4167>
- Nwamekwe, C. O., Ewuzie, N. V., Okpala, C. C., Ezeanyim, C., Nwabueze, C. V., & Nwabunwanne, E. C. (2025). Optimizing Machine Learning Models for Soil Fertility Analysis: Insights from Feature Engineering and Data Localization. *Gazi University Journal of Science Part A: Engineering and Innovation*, 12(1), 36-60. <https://dergipark.org.tr/en/pub/gujisa/issue/90827/1605587>
- Nwamekwe, C. O., Ewuzie, N.V., Igbokwe, N. C., Nwabunwanne, E. C., & Ono, C. G. (2025). Digital Twin-Driven Lean Manufacturing: Optimizing Value Stream Flow. *Letters in Information Technology Education (LITE)*, 8 (1), pp.1-13. <https://hal.science/hal-05127340/>
- Nwamekwe, C. O., Okpala, C. C., and Okpala, S. C., (2024). Machine Learning-Based Prediction Algorithms for the Mitigation of Maternal and Fetal Mortality in the Nigerian Tertiary Hospitals. *International Journal of Engineering Inventions*, 13(7), PP: 132-138. <https://www.ijejournal.com/papers/Vol13-Issue7/1307132138.pdf>
- Nwaulune, J. (2024). Investigating the adoption of green logistics practices on operational sustainability in fast-moving customer goods in Lagos state, Nigeria. *Journal of Economics Finance and Management Studies*, 07(07). <https://doi.org/10.47191/jefms/v7-i7-42>
- Nwokolo, S., Meyer, E., & Ahia, C. (2023). Credible pathways to catching up with climate goals in Nigeria. *Climate*, 11(9), 196. <https://doi.org/10.3390/cli11090196>
- Ogunmodede, E., Aggreh, M., & Udeh, N. (2024). Firms' attributes and sustainability disclosures: a study of sensitive environmental sector in Nigeria. *African Journal of Accounting and Financial Research*, 7(3), 130-148. <https://doi.org/10.52589/ajaf-ri-nuwbri1f>

- Ohiomah, I. and Aigbavboa, C. (2020). Identifying barriers of sustainable construction: a Nigerian case study. *Matec Web of Conferences*, 312, 04004. <https://doi.org/10.1051/mateconf/202031204004>
- Okeagu F. N., Charles Onyeka Nwamekwe, Blessing Precy Nnamani. (2024). Challenges and Solutions of Industrial Development in Anambra State, Nigeria. *Iconic Research and Engineering Journals*, 7(11), 467-472. <https://www.irejournals.com/formatedpaper/1705825.pdf>
- Okpala C. C., Chukwudi Emeka Udu, & Charles Onyeka Nwamekwe. (2025). Sustainable HVAC Project Management: Strategies for Green Building Certification. *International Journal of Industrial and Production Engineering*, 3(2), 14-28. <https://journals.unizik.edu.ng/ijipe/article/view/5595>
- Okpala, C. C., Ezeanyim, O. C., & Nwamekwe, C. O. (2024). The Implementation of Kaizen Principles in Manufacturing Processes: A Pathway to Continuous Improvement. *International Journal of Engineering Inventions*, 13(7), 116-124. <https://www.ijejournal.com/papers/Vol13-Issue7/1307116124.pdf>
- Okpala, C. C., Udu, C. E., & Nwamekwe, C. O. (2025). Artificial Intelligence-Driven Total Productive Maintenance: The Future of Maintenance in Smart Factories. *International Journal of Engineering Research and Development (IJERD)*, (21)1, 68-74. <https://www.ijerd.com/paper/vol21-issue1/21016874.pdf>
- Oláh, J., Aburumman, N., Popp, J., Khan, M., Haddad, H., & Kitukutha, N. (2020). Impact of industry 4.0 on environmental sustainability. *Sustainability*, 12(11), 4674. <https://doi.org/10.3390/su12114674>
- Onuoha, N. and Okoye, G. (2020). Assessment of the level of realization of sustainable development goals: evidence from manufacturing firms in Nigeria. *Advances in Social Sciences Research Journal*, 7(3), 330-340. <https://doi.org/10.14738/assrj.73.7980>
- Patrick, N., Eyinna, D., & Stanley, K. (2022). Assessment of health and safety risk among waste scavengers in Enugu state, Nigeria. *Asian Research Journal of Arts & Social Sciences*, 23-37. <https://doi.org/10.9734/arjass/2022/v16i230281>
- Pell, R., Tijsseling, L., Goodenough, K., Wall, F., Dehaine, Q., Grant, A., ... & Whattoff, P. (2021). Towards sustainable extraction of technology materials through integrated approaches. *Nature Reviews Earth & Environment*, 2(10), 665-679. <https://doi.org/10.1038/s43017-021-00211-6>
- Qiu, R., Hou, S., Chen, X., & Meng, Z. (2021). Green aviation industry sustainable development towards an integrated support system. *Business Strategy and the Environment*, 30(5), 2441-2452. <https://doi.org/10.1002/bse.2756>
- Rabia, M., Aldosari, E., & Geneidy, A. (2024). Exceptionally crystalline nature of cro3-cr2o3/ppy nanocomposite as a prospective photoelectrode for efficient green hydrogen generation in the context of environmentally friendly water-splitting reactions using sanitized water. *Environmental Progress & Sustainable Energy*, 43(5). <https://doi.org/10.1002/ep.14455>
- Richard, M., Fadeyi, O., & Samuel, T. (2021). Green entrepreneurship and employment generation in a developing nation: the Nigerian case. *Journal of Humanities Arts and Social Science*, 5(1), 81-88. <https://doi.org/10.26855/jhass.2021.01.009>

- Saxena, A., Bansal, D., & Tiwari, S. (2023). Industry 5.0 contribution to sustainable development: a roadmap for environmental sustainability., 131-146. https://doi.org/10.48001/978-81-966500-9-4_11
- Shurrab, J., Hussain, M., & Khan, M. (2019). Green and sustainable practices in the construction industry. *Engineering Construction & Architectural Management*, 26(6), 1063-1086. <https://doi.org/10.1108/ecam-02-2018-0056>
- Siddique, I. (2024). Sustainable manufacturing practices: reducing waste and energy consumption in production systems. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.4919617>
- Singh, S., Giudice, M., Jabbour, C., Latan, H., & Sohal, A. (2021). Stakeholder pressure, green innovation, and performance in small and medium-sized enterprises: the role of green dynamic capabilities. *Business Strategy and the Environment*, 31(1), 500-514. <https://doi.org/10.1002/bse.2906>
- Tan, L., Yang, Z., Irfan, M., Ding, J., Hu, M., & Hu, J. (2023). Toward low-carbon sustainable development: exploring the impact of digital economy development and industrial restructuring. *Business Strategy and the Environment*, 33(3), 2159-2172. <https://doi.org/10.1002/bse.3584>
- Tripathi, V., Chattopadhyaya, S., Mukhopadhyay, A., Sharma, S., Singh, J., Pimenov, D., ... & Giasin, K. (2021). An innovative agile model of smart lean-green approach for sustainability enhancement in industry 4.0. *Journal of Open Innovation Technology Market and Complexity*, 7(4), 215. <https://doi.org/10.3390/joitmc7040215>
- Ugwu, C., Ozoegwu, C., & Ozor, P. (2020). Solid waste quantification and characterization in university of Nigeria, Nsukka campus, and recommendations for sustainable management. *Heliyon*, 6(6), e04255. <https://doi.org/10.1016/j.heliyon.2020.e04255>
- Ullah, A., Bavorová, M., Shah, A., & Kandel, G. (2024). Climate change and rural livelihoods: the potential of extension programs for sustainable development. *Sustainable Development*, 32(5), 4992-5004. <https://doi.org/10.1002/sd.2951>
- Umar, M., Khan, S., Zia-ul-haq, H., Yusliza, M., & Farooq, K. (2021). The role of emerging technologies in implementing green practices to achieve sustainable operations. *The TQM Journal*, 34(2), 232-249. <https://doi.org/10.1108/tqm-06-2021-0172>
- Uzoamaka, N. and Yvette, C. (2023). Corporate planning and sustainability of small and medium scale enterprises in Anambra state, Nigeria. *Journal of Economics Finance and Management Studies*, 06(05). <https://doi.org/10.47191/jefms/v6-i5-11>
- Vasconcelos, D., Viana, F., & Neto, J. (2019). Lean and green: the contribution of lean production and environmental management to the waste reduction. *Revista De Administração Da Ufsm*, 12(2), 365-383. <https://doi.org/10.5902/1983465921750>
- Wang, C., Zhang, S., & Zhang, X. (2022). How to embrace sustainable performance via green learning orientation: a moderated mediating model. *Sustainability*, 14(13), 7933. <https://doi.org/10.3390/su14137933>
- Wellbrock, W., Ludin, D., Röhrle, L., & Gerstlberger, W. (2020). Sustainability in the automotive industry, importance of and impact on automobile interior – insights from an empirical survey. *International Journal of Corporate Social Responsibility*, 5(1). <https://doi.org/10.1186/s40991-020-00057-z>

- Yacob, P., Wong, L., & Khor, S. (2019). An empirical investigation of green initiatives and environmental sustainability for manufacturing SMEs. *Journal of Manufacturing Technology Management*, 30(1), 2-25. <https://doi.org/10.1108/jmtm-08-2017-0153>
- Yakubu, B., Salamzadeh, A., Bouzari, P., Ebrahimi, P., & Fekete-Farkas, M. (2022). Identifying the key factors of sustainable entrepreneurship in the Nigerian food industry: the role of media availability. *Entrepreneurial Business and Economics Review*, 10(2), 147-162. <https://doi.org/10.15678/eber.2022.100209>
- Yusuf, R., Sawyerr, H., Adeolu, A., Habeeb, L., & Abolayo, T. (2018). Seroprevalence of hepatitis b virus and compliance to standard safety precautions among scavengers in Ilorin metropolis, Kwara state, Nigeria. *Journal of Health and Pollution*, 8(19). <https://doi.org/10.5696/2156-9614-8.19.180914>